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The profit maximizing liner shipping problem with flexible frequencies: logistical and environmental considerations

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A synthesis of work on

- A recent MSc. thesis at DTU*
- Air emissions from ships (mainly GHGs)
- Speed optimization in maritime transport

FOCUS: CONTAINER SHIPPING

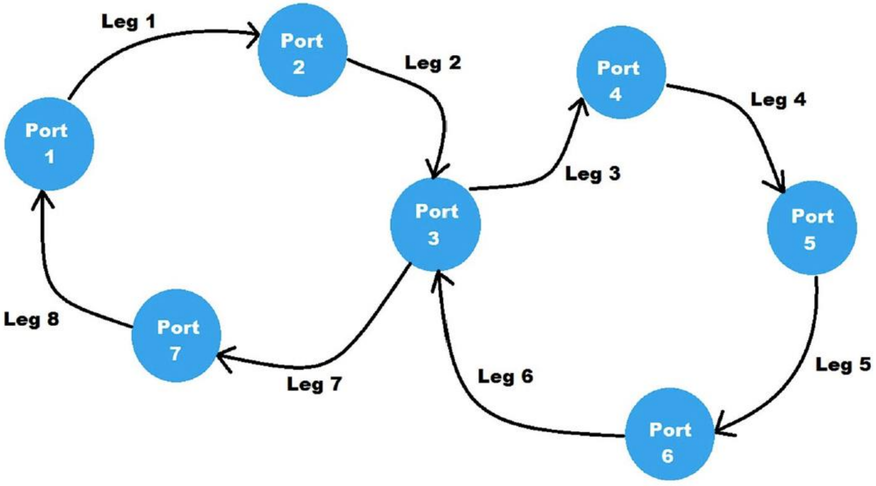
* Massimo Giovannini, “Speed Optimization and Environmental Effect in Container liner Shipping”, MSc. Thesis, DTU, 2017.

A tactical level ‘fixed route’ problem

- Assumes a fleet of *N* identical containerships deployed on a given **fixed route**
  - Can be generalized to non-identical ships

- **WHAT IS OPTIMIZED?**
- Maximize the **average per day profit** of the carrier.

- Any route topology can be examined



OVERVIEW

Model examines

Effect of:

- Bunker price
- Freight rates
- In transit cargo inventory costs

Effect on:

- Ship speeds
- Number of ships
- Service frequency

OVERVIEW

Model examines

Effect of:

- Bunker price
- Freight rates
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Effect on:

- Ship speeds
- Number of ships
- Service frequency

ALSO:

- Profits
- CO2 emissions

Problem inputs

- The route geometry, represented by a set of ports and a set of legs representing the route.
- The lengths of each leg of the route.
- The freight rate of transporting a TEU from a port on the route to another port on the route, for all relevant port pairs (assumed exogenous).
- The demand in TEUs from a port on the route to another port on the route, for all relevant port pairs.
- The bunker price.
- The daily operating costs of each vessel, other than fuel.
- The daily at sea fuel consumption function as a function of ship speed.
- The daily at port fuel consumption.
- The average monetary value of ship cargo on each leg of the route.
- The operator's annual cost of capital.
- The time spent at each port.
- The cargo handling cost per TEU.
- The capacity of each vessel.
- The minimum and maximum allowable ship speeds.

Main decision variables: 3

- Number of ships *N* deployed on the route.
- Ship speeds along each leg of the route.
- Service frequency.

NOTE: service frequency is typically assumed **FIXED** (and typically ONCE A WEEK)

IN OUR MODEL it is allowed **TO VARY** (be a decision variable)

Mathematical formulation

$$\dot{\pi} = Max_{v_i,t_0,N}\left\{\frac{1}{t_0}\left(\sum_x\sum_z F_{zx}c_{zx} - P\sum_i f(v_i)\frac{L_i}{24v_i} - PA\sum_j G_j - \sum_i \alpha_i C_i\frac{L_i}{24v_i} - H\sum_j D_j\right) - NE\right\} \tag{9}$$

subject to the following constraints:

$$v_{min} \leq v_i \leq v_{max} \quad i \in I \tag{10}$$

$$Nt_0 = \sum_i \frac{L_i}{24v_i} + \sum_j G_j \tag{11}$$

and

$$N \in \mathbb{N}^+. \tag{12}$$

Mathematical formulation

Revenue Fuel cost (sea) Fuel cost (port) Inventory cost

$$\dot{\pi} = Max_{v_i,t_0,N}\left\{\frac{1}{t_0}\left(\sum_x \sum_z F_{zx}c_{zx} - P\sum_i f(v_i)\frac{L_i}{24v_i} - PA\sum_j G_j - \sum_i \alpha_i C_i \frac{L_i}{24v_i} - H\sum_j D_j\right) - NE\right\} \tag{9}$$

Cargo handling cost OPEX

subject to the following constraints:

$$v_{min} \leq v_i \leq v_{max} \quad i \in I \tag{10}$$

$$Nt_0 = \sum_i \frac{L_i}{24v_i} + \sum_j G_j \tag{11}$$

and

$$N \in \mathbb{N}^+. \tag{12}$$

Key equation

$$Nt_0 = \sum_i \frac{L_i}{24v_i} + \sum_j G_j$$

Key equation- inputs

Route leg lengths

$$Nt_0 = \sum_i \frac{L_i}{24v_i} + \sum_j G_j$$

Port times

Key equation- decision variables

\# ships

Service period (=1/frequency)

$$Nt_0 = \sum_i \frac{L_i}{24v_i} + \sum_j G_j$$

Speeds at legs

1st Observation

- If frequency of service is **FIXED** (eg, service once a week), line has **ONE** degree of freedom: it can only play with N (number of ships) and the speeds.

- One degree of freedom will generally **restrict the feasible solution space** and will generally **entail a cost**.

- If on the other hand service frequency is **FLEXIBLE**, a wider set of alternatives may be available to the line, and these may be more profitable.

2nd observation:
BOTH obj. fcn. and constraints are NONLINEAR

$$\dot{\pi} = Max_{v_i,t_0,N}\left\{\frac{1}{t_0}\left(\sum_x\sum_z F_{zx}c_{zx} - P\sum_i f(v_i)\frac{L_i}{24v_i} - PA\sum_j G_j - \sum_i \alpha_i C_i \frac{L_i}{24v_i} - H\sum_j D_j\right) - NE\right\} \tag{9}$$

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$$Nt_0 = \sum_i \frac{L_i}{24v_i} + \sum_j G_j \tag{11}$$

and

$$N \in \mathbb{N}^+. \tag{12}$$

Objective function is a ratio

- MAXIMIZE

  TOTAL ROUTE PROFIT / ROUTE DURATION

- Both numerator and denominator are nonlinear functions of ship speed

- And so is the ratio itself

Linearization

- Follow approach by Wang and Meng (2012)
- Obtain piecewise linear approximation
- Code in MATLAB
- Use Excel Solver

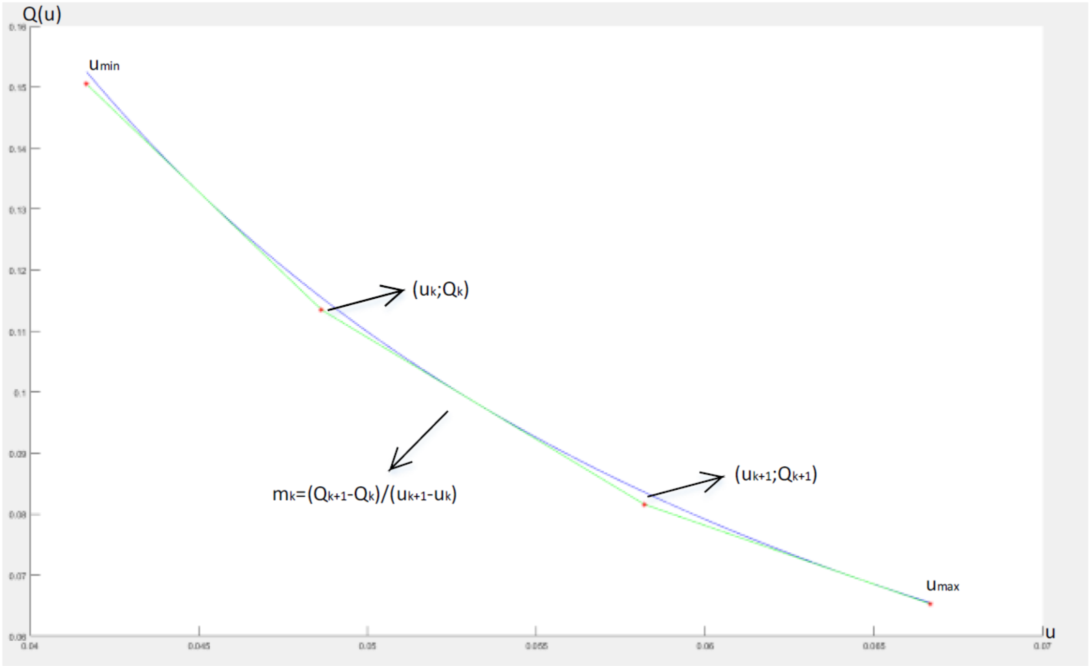


Figure 4.134: Example of the piecewise linear function in MATLAB

Scenario examined

Mainlane East- West

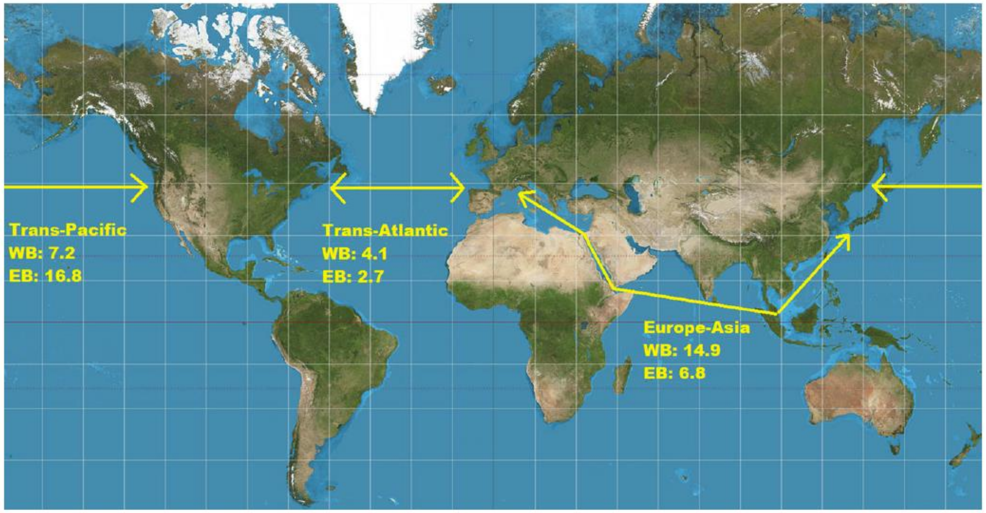


Fig. 4 Container flows on Mainlane Eas--West route [million TEUs], 2015. WB: westbound, EB: eastbound. Adapted from UNCTAD (2016), Table 1.7

3 main lanes

- Transpacific lane counts for 46% of the overall container trade on the East-West route
- Europe-Asia lane counts for 41% of the trade
- Transatlantic lane counts for 13% of the trade (UNCTAD, 2016).

Trade imbalances

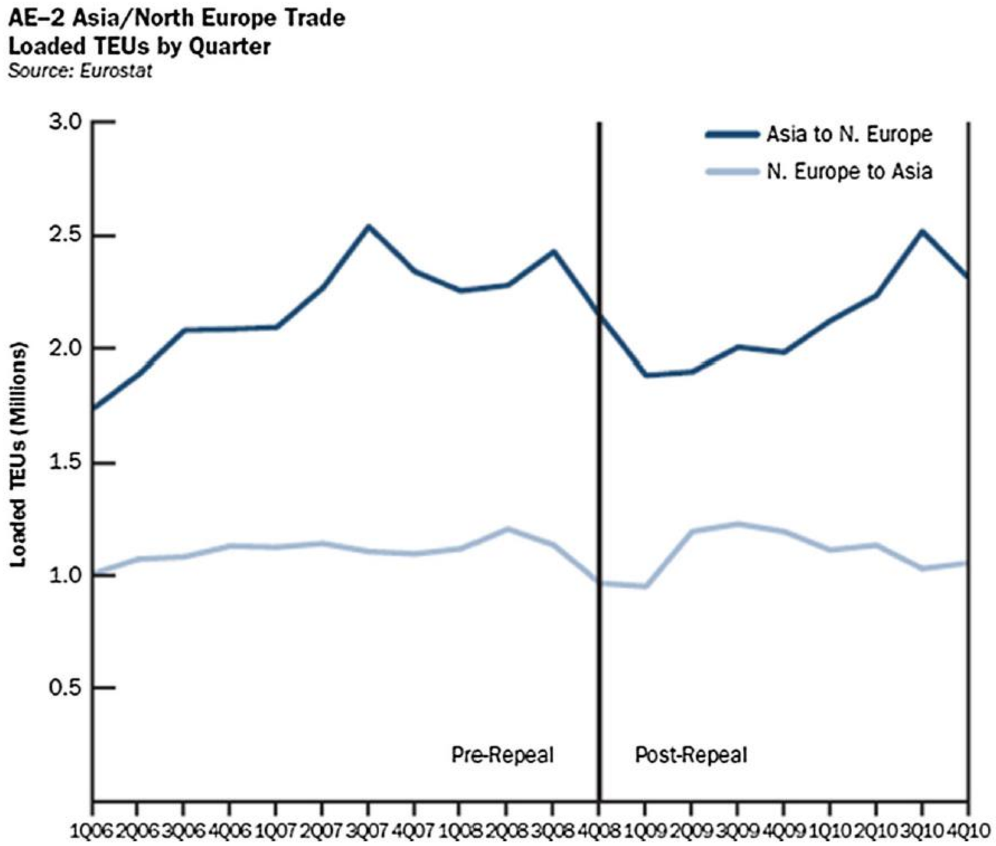


Fig. 3 Trade imbalances between Far East and Europe. The vertical line in 4Q08 is the repeal of EU Regulation 4056/86 in 2008. *Source* FMC (2012)

Freight rate imbalances

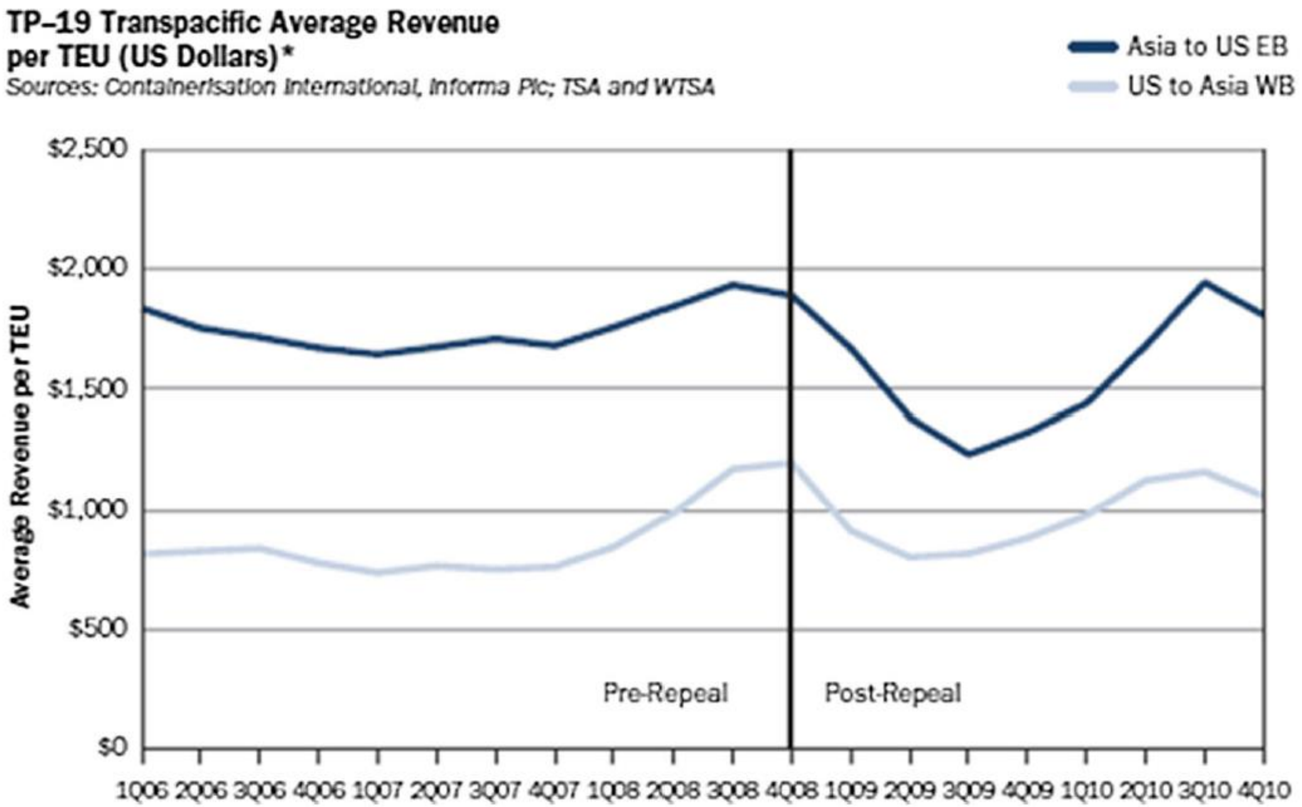


Fig. 2 Freight rate imbalances between Asia and the US. The vertical line in 4Q08 is the repeal of EU Regulation 4056/86 in 2008. *Source* FMC (2012)

Routes examined

- AE2: North Europe and Asia: such service links Asia to North Europe and is provided by Maersk. The same service is also provided by MSC under the name SWAN.
- NEUATL1: North Europe and North America (East Coast): links North Europe to the US East Coast. The service is furnished by MSC or similarly by Maersk under the name TA1.
- TP1: North America (West Coast) and Asia: the route connects Asia to the West Coast of North America. Maersk offers this service. Same service is also provided by MSC and it is called EAGLE.

Table 3 Ports in the routes under study

Ports					
AE2		TP1		NEUATL1	
Felixstowe	1	Vancouver	1	Antwerp	1
Antwerp	2	Seattle	2	Rotterdam	2
Wilhelmshaven	3	Yokohama	3	Bremerhaven	3
Bremerhaven	4	Busan	4	Norfolk	4
Rotterdam	5	Kaoshiung	5	Charleston	5
Colombo	6	Yantian	6	Miami	6
Singapore	7	Xiamen	7	Houston	7
Hong Kong	8	Shanghai	8	Norfolk	8
Yantian	9	Busan	9		
Xingang	10				
Qingdao	11				
Busan	12				
Shanghai	13				
Ningbo	14				
Yantian	15				
Tanjung Pelepas	16				
Algeciras	17				

Sources of data

- UNCTAD www.unctad.org for general information on liner shipping statistics
- EQUASIS (2015), database with information on the world merchant fleet in 2015
- FMC (2012) for transport demand tables, capacity utilization on various trade lanes
- Drewry (2015) for miscellaneous vessel operating cost information
- Maersk Line www.maersk.com for information on routes and schedules including port times
- https://shipandbunker.com/prices for bunker price information
- www.shipowners.dk/en/services/beregningsvaerktoejer, for the SHIP DESMO spreadsheet that calculates fuel consumption and emissions as a function of speed- developed for Danish Shipping
- www.worldfreightrates.com for freight rate information
- www.searates.com for distances among ports
- www.marinetraffic.com for information on ship deadweight, length overall and breadth
- www.containership-info.com for information on ship power.

3 scenarios

	#Ships	Speeds	Frequency
• No. 1			
• No. 2			
• No. 3			

3 scenarios

	#Ships	Speeds	Frequency
• No. 1	variable	variable	fixed
• No. 2			
• No. 3			

3 scenarios

	#Ships	Speeds	Frequency
• No. 1	variable	variable	fixed
• No. 2	fixed	variable	variable
• No. 3			

3 scenarios

	#Ships	Speeds	Frequency
• No. 1	variable	variable	fixed
• No. 2	fixed	variable	variable
• No. 3	variable*	variable	variable

*with an upper bound

1st KEY FINDING

FREQUENCY OF ONE CALL PER WEEK NOT NECESSARILY OPTIMAL

Requiring frequency to be one call per week may restrict feasible solution space and will generally entail a cost.

Set of allowable service periods (days):

S={3.5, 4, 5, 6, 7, 8, 9, 10, 14}

Flexible frequencies

- **S={3.5, 4, 5, 6, 7, 8, 9, 10, 14}**

Flexible frequencies

- **S={3.5, 4, 5, 6, 7, 8, 9, 10, 14}**
- (weekly service)

Flexible frequencies

- **S={3.5, 4, 5, 6, 7, 8, 9, 10, 14}**
- (biweekly service)

Flexible frequencies

- **S={3.5, 4, 5, 6, 7, 8, 9, 10, 14}**

- (twice a week service)

Flexible frequencies

- **S={3.5, 4, 5, 6, 7, 8, 9, 10, 14}**
- ???
- (this week Sunday, next week Saturday, following week Friday, etc)

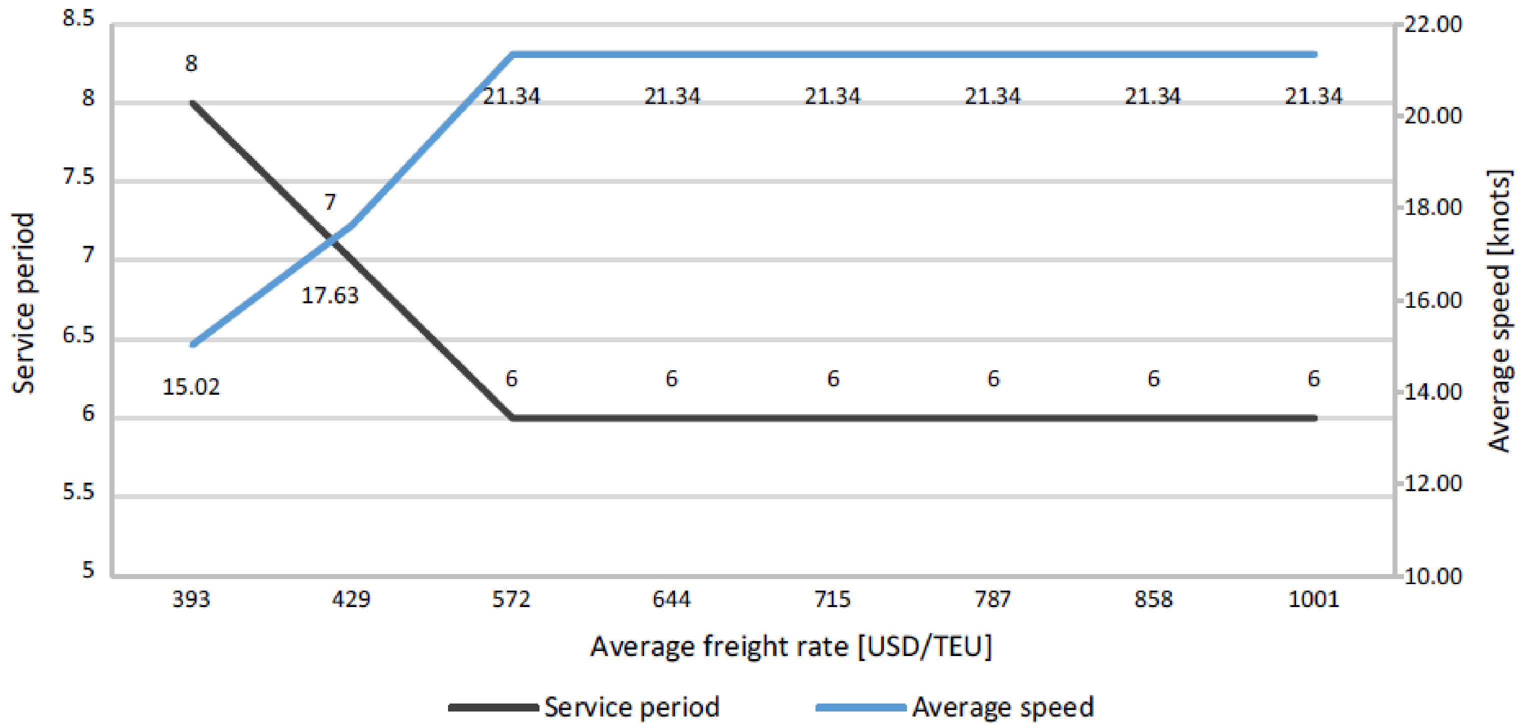


Fig. 8 Fixed number of ships scenario, optimal service period and optimal average speed at different average freight rates (route TP1)

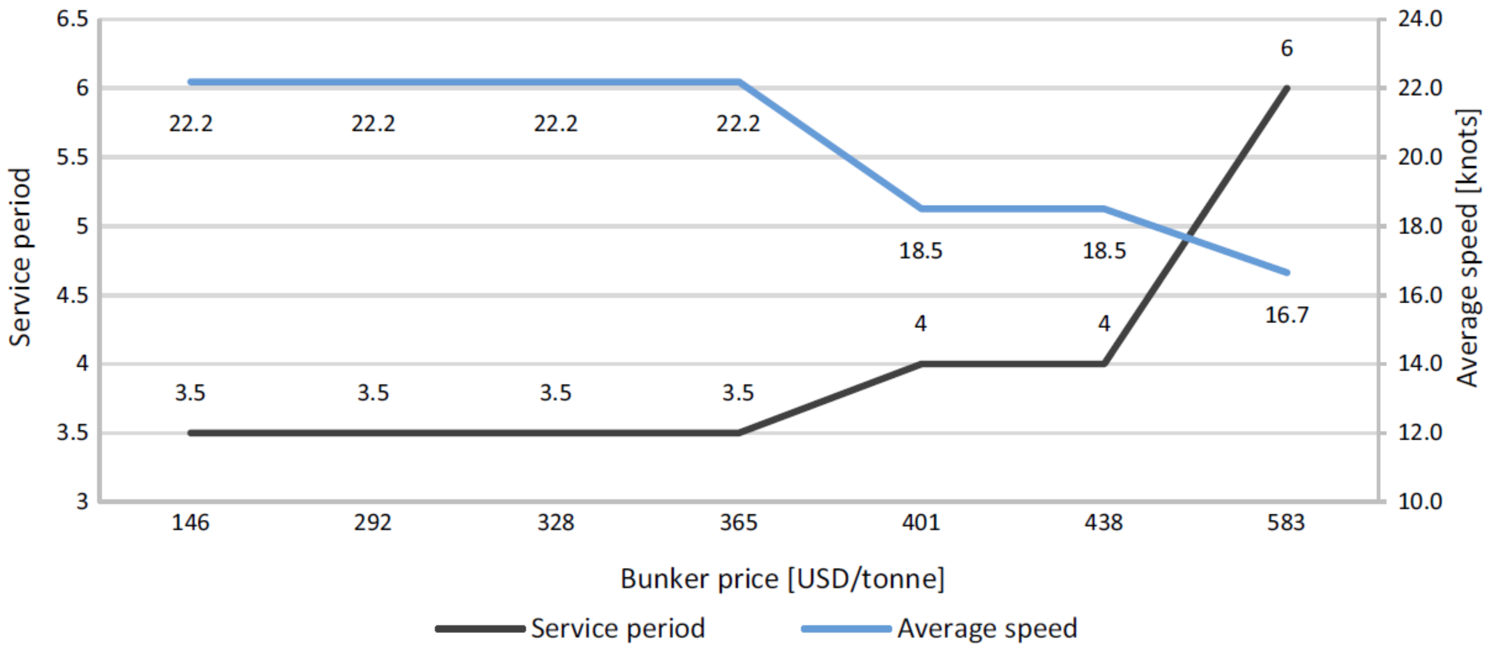


Fig. 10 Number of ships bounded above scenario, optimal service period and optimal average speed at different bunker prices (route AE2)

Cost of forcing a weekly frequency

Instance	Average freight rate (USD/TEU)	Optimal t_0 (days)	Δ (USD/day)
1	393	8	4,132
2	429	7	0
3	572	6	15,717
4	644	6	35,029
5	715	6	54,341
6	787	6	73,653
7	858	6	92,965
8	1,001	6	131,590

Explanation

Low freight rates

- Enforcing a weekly frequency **(higher than the optimal one)**
  - Requires a speed higher than the optimal one
  - Increased revenue is lower than increased cost

High freight rates

- Enforcing a weekly frequency **(lower than the optimal one)**
  - Requires a speed lower than the optimal one
  - Reduced revenue is higher than reduced cost

Can flexible frequencies work?

- As things stand today, NO WAY!
- BUT!
- Why not?

Can flexible frequencies work?

- As things stand today, NO WAY!
- BUT!
- Why not?

- Is weekly freq. in the Bible?
- Is weekly freq. mandated by law?
- Or is it just the force of habit?

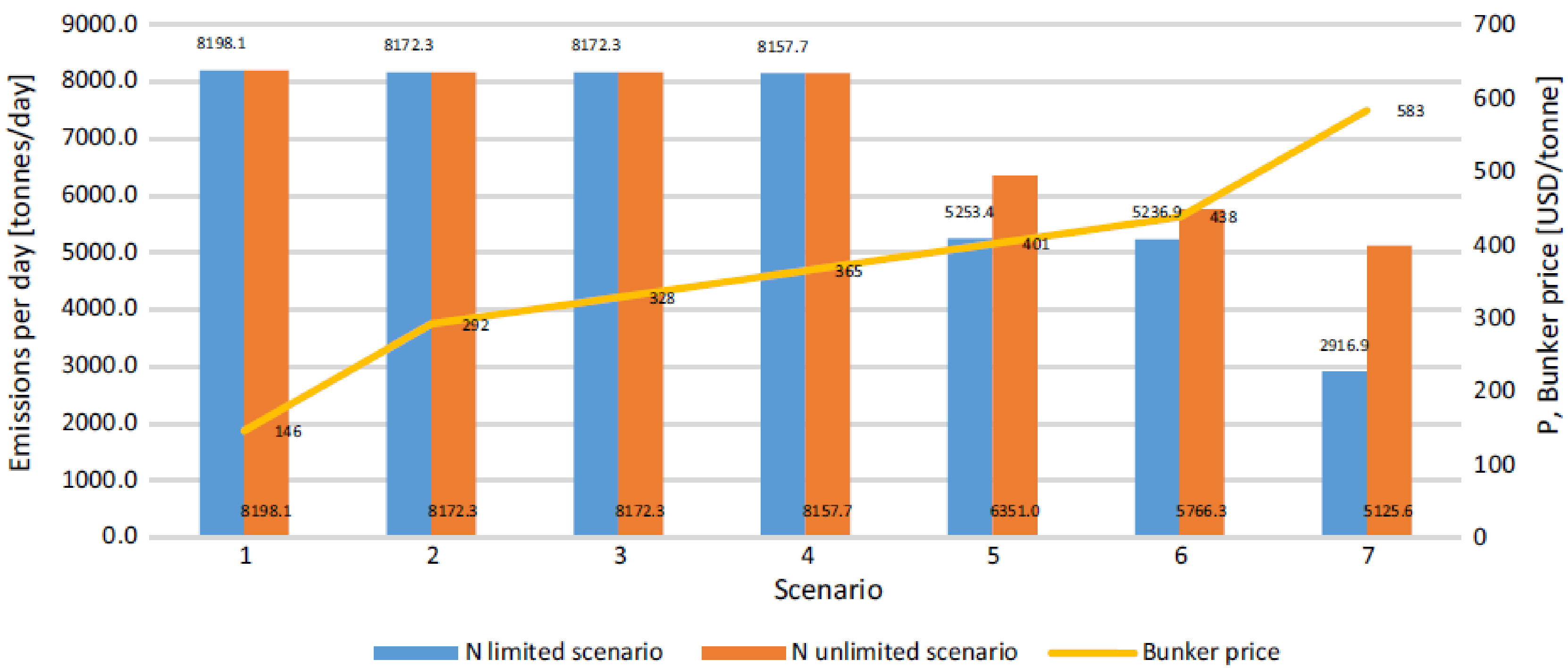
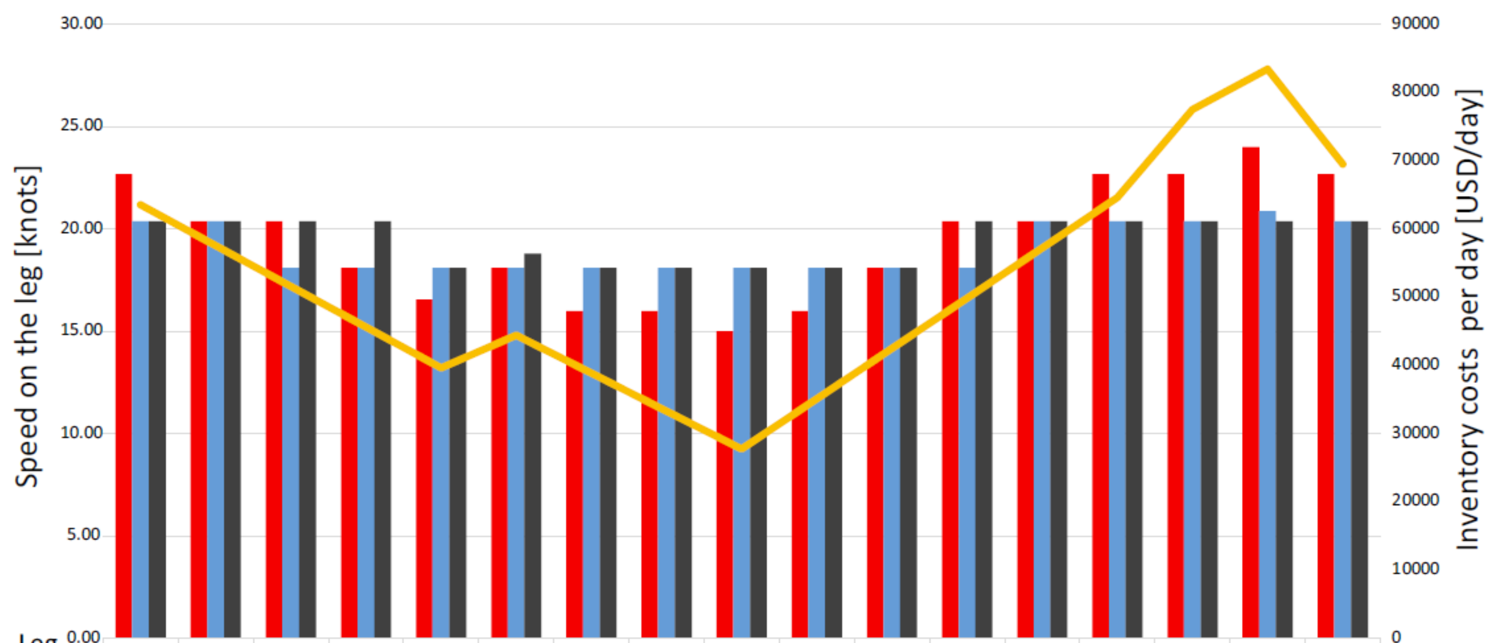


Fig. 13 Comparison between the *N* limited scenario and the *N* unlimited scenario, effect of the bunker price on the daily CO_2 emissions (route AE2)



Leg	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Scenario 1	22.68	20.38	20.38	18.10	16.55	18.10	15.99	15.99	15.00	15.99	18.10	20.38	20.38	22.68	22.68	24.00	22.68
Scenario 2-base	20.38	20.38	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	20.38	20.38	20.38	20.88	20.38
Scenario 3	20.38	20.38	20.38	20.38	18.10	18.80	18.10	18.10	18.10	18.10	18.10	20.38	20.38	20.38	20.38	20.38	20.38
Daily inventory costs	63533	57564	51594	45625	39655	44446	38891	33335	27779	35141	42503	49865	57226	64588	77506	83403	69503

Fig. 15 Effect of inventory costs and bunker price on the optimal speeds (route AE2). The speeds are higher on the legs on which the daily inventory costs are higher

PARENTHESIS

IMO GHG discussion

- Chile and Peru objected to ”speed reduction” as a measure.
- Argued that sending cherries to China would suffer.
- Suggested using ”speed optimization” instead

Compromise solution

- Both ”speed optimization” and ”speed reduction” were included in the text

IMO wording

.4 consider and analyse the use of speed optimization and speed reduction as a measure, taking into account safety issues, distance travelled, distortion of the market or trade and that such measure does not impact on shipping's capability to serve remote geographic areas;

- But no one is really sure what is meant by ”speed optimization”!

A look at the facts

Source: ShipCLEAN project (2018)

EASTBOUND: Xiamen, Ningbo, Shanghai, Manzanillo, Buenaventura, Callao, San Antonio

WESTBOUND: Callao, Manzanillo, Kaohsiung, Yantian, Hong Kong, Xiamen

Observation: Speed reduction BIG TIME

Source: ShipCLEAN project (2018)

EASTBOUND: Xiamen, Ningbo, Shanghai, Manzanillo, Buenaventura, Callao, San Antonio

WESTBOUND: Callao, Manzanillo, Kaohsiung, Yantian, Hong Kong, Xiamen

Conclusions

- Optimization of logistics services can play an important role in emissions reduction
- Under certain circumstances, win-win scenarios can be realized
- A fixed service frequency is not necessarily optimal in liner shipping
- Tools like this can be used to explore logistical measures to reduce CO2

Recent papers

Marit Econ Logist
https://doi.org/10.1057/s41278-018-0098-8

ORIGINAL ARTICLE

Decarbonization of maritime transport: to be or not to be?

Harilaos N. Psaraftis[1]

Recent papers ii

European Journal of Operational Research 000 (2018) 1–17

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Invited Review

The role of operational research in green freight transportation

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Thank you very much!

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